

A REVIEW ON RESIDUAL STRESS IN MANUFACTURED COMPONENT, TESTING TECHNIQUES, AND RELIEVING METHODS

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ABSTRACT

Residual stress is the stress that stays behind in a body after any external forces or thermal gradients are removed. Due to manufacturing processes residual stresses generated near the surface of the finished component. Properties of the component that are influenced by residual stress consist of fatigue strength, corrosion behavior and distortion of parts. This paper reviews the residual stress profile generated by different manufacturing processes. Measuring residual stress is also very important. Destructive, Non-destructive and semi-destructive methods classified. For the better life of the machined component, it is suggested to stress relief the generated stress. There is mechanical, heat and diffusion treatment available to relieve the stress. Residual stress measuring techniques classified and reviewed. Also, the vibratory stress relief technique briefly reviewed.

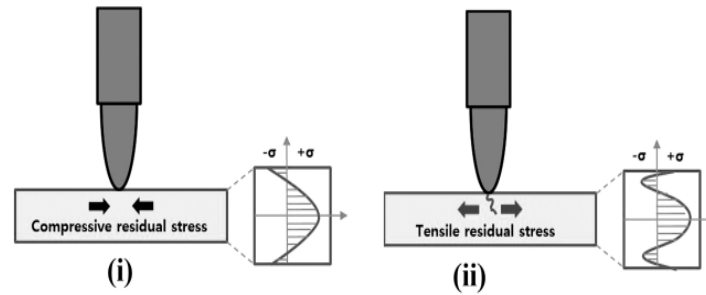
KEYWORDS: Residual Stress, Manufacturing Process, Measuring Residual Stress, Stress Relief & Vibratory Stress Relief

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INTRODUCTION

In the production process, one product undergoes with several machining processes. In that, metal cutting is one of the main process and widely used. There are certain forces acting on the surface where there is contact between the cutting tool and the surface. While the component in the machining process certain stress induced in the body due to the forces acting on the body, this stress remains in the body after completion of the machining process. The stresses which remained in the body after complete removal of external acting forces are termed as the residual stress.

Residual stresses in the machined component are one of the useful roles in the recital of machined parts. The different characteristics which influenced by the induced residual stress are the deformation of the parts, resistance towards corrosion, fatigue strength, surface hardness etc. Due to the residual stress, the strength of the component either improved or it becomes weak. Hence, it becomes one of the important features of machining. The residual stresses are induced by various causes. Out of which some can be listed are plastic deformation, volumetric change, and thermal gradient. As in plastic deformation, there are permanent changes in the crystal structure takes place [1]. The residual stresses induced by thermal gradients are due to volumetric change in the material.



**Figure 1: (i) Compressive Residual Stresses in Layer
(ii) Tensile Residual Stresses in Layer**

$$\text{Total Stress} = \text{Stress Due to External Load} + \text{Residual Stress}$$

LITERATURE

Manufacturing Process and Residual Stress

Turning

Y.B. Guoa et.al [4] has studied and compared the residual stress induced after hard turning and grinding process. He significantly presented stress profile against the load applied and material used

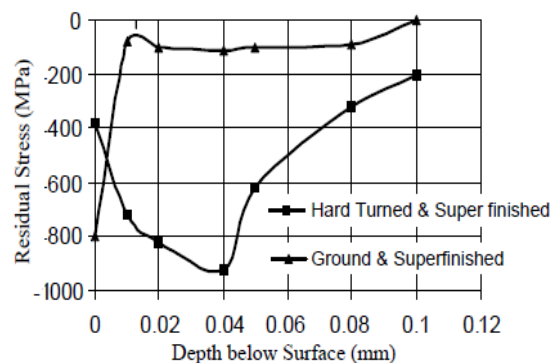


Figure 2: Process-Induced Residual Stresses vs. Depth Below the Surface

The compressive residual stress induced in hard turning was deep as compared in grinding with achieved Surface finish was an equivalent. Also, it is found that compressive residual stress and its effective depth were influencing factors fatigue damage. For these study researchers developed a new simulation model of rolling contact for hard machined components.

Nerea Ordas et.al [5] has presented residual stress profile generated in hard steel (AISI D2) after turning process. The hardness of the specimen was 60 HRC. The residual stresses before hard turning process also generated. The four parameters selected for this study was two different wore state tools, speed, feed rate and depth of cut. There is no coolant used, and it was dry cutting. Both macroscopic and microscopic residual stresses were investigated. The study concluded that compressive stress generated was low in magnitude and depth wise it was shallow for the new tool as a comparative worn tool. The reason for this friction area, there is a small friction area for a new tool. It can be observed that plastic deformation was the governing factor, in residual stress, then the temperature for that test specimen. The RIM method has one of the commanding tools in triaxial residual stress analysis.

G.F. Batalha et.al [6] studied cutting conditions on the cutting forces as well as on the residual stresses. For the study conical bearings used by researchers. The test specimens temper and quenched with 60 to 64 HRC hardness. On the other hand, he put efforts on finding influence the cutting parameters on the microstructure of the material and its association with the residual stress. For experiment regular turning machine and CBN inserts was used. It was found that cutting force was an important factor in generation residual stress. Residual stress subjective to not only feed rate but the cutting depth.

J.C. Outeiro [7] has studied turning machining conditions on surface integrity. For this study, the materials used are Inconel 718 and stainless steel. The tools used for turning were coated and uncoated carbide tools. Both the materials are intricate to-machine due to their inbuilt mechanical and thermal properties. This results from very high cutting force causing high local heat around cutting edge. This induces high tensile residual stress. The diversity observed due to the variation of the tribological conditions of work material. The uncut chip thickness has a strong influence on the residual stresses.

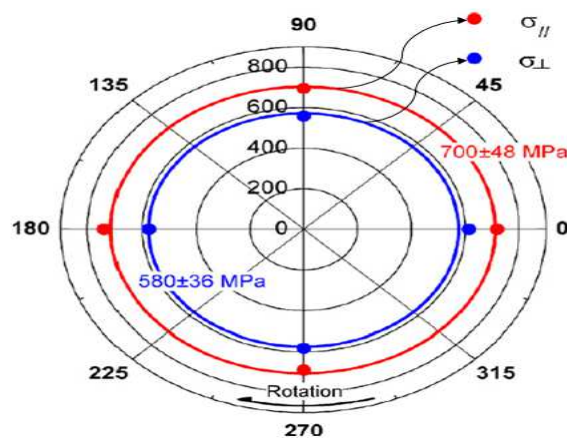


Figure 3: Residual Stresses on the Machined Transient Surface

M. Mohammadpour et.al [8] has presented a Finite Element Model for orthogonal cutting of mild steel. The FE model is based on the Lagrangian formulation. The researchers have validated the study by comparing results with experiments available in the earlier experiments conducted (from literature) by other researchers. Chip formation simulation and its distribution of stress were achieved here.

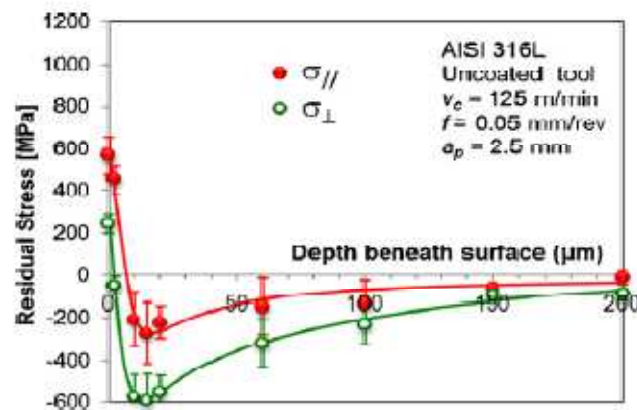


Figure 4: Residual Stresses Distributions in Machined Surface

The FEA Model was validated by evaluation of residual stress profiles in circumferential and axial orders with actual values available and shown as per the below figure 5

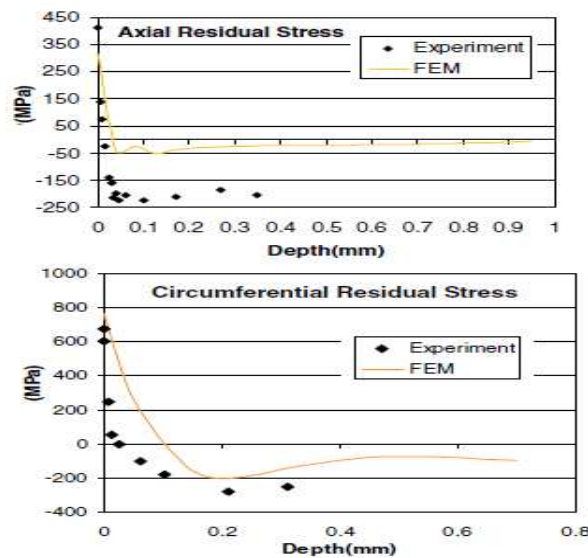


Figure 5: FEM vs. Experimental Results Comparison

Franci Pusavec [9] has presented the residual stresses generated during the cryogenic turning method. The material used in this study was Inconel 718. CNC turning on Inconel 718 material was used for this study. For experiments, four following conditions were used,

- Dry machining (dry),
- Minimum quantity lubrication (MQL–120 ml/h).
- Cryogenic machining (0.6 kg=min per nozzle) 4. 4. Combination cryo +MQL machining.

The result of cryogenic machining showed that it generates superior compressive residual stresses. At deeper levels below the machined surface. The figure 6 shows the residual stress profile under cryogenic turning.

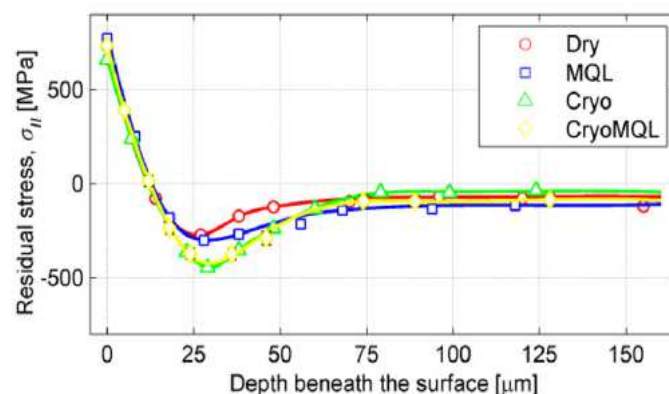


Figure 6: Residual Stress Profile after Cryogenic Turning

Caixu Yue [10] has experimentally studied the sound effects of unusual machining parameters and tool geometry on surface residual stress and affected layer of the machined component by residual stress. In this research work, high strength tool steel (Cr12MoV) with of hardness 60-62 HRC used as test material. The research works summarized the

effect of surface finish; tool nose radius and tool wear on residual stress. Under hard turning, frictional heat increases the temperature of workpiece and tool. The surface of workpiece exceeds the phase transformation temperature of the workpiece. Due to that level of tissue, causing the stress field change. Therefore the turned surface is under compressive residual stress. The results that smaller the nose radius, higher the compressive residual stress. With an increase in cutting speed increases, the surface compressive residual stress rate also influences the depth of the layer.

Borja Coto [11] has analyzed the cutting conditions on the residual stresses generated during the turning process. Residual stresses were tested by the X-ray diffraction and the $\sin^2\psi$ method. Cutting conditions used in this study were cutting speed, feed rate & depth of cut. Residual stress state was estimated by the maximum & minimum principal stress ($\sigma_{\max}$) & ($\sigma_{\min}$). Mohr's circle were used & roughness, Ra, was analyzed. The analysis of variance (ANOVA) has been done to recognize most influencing factor from the cutting conditions. From this study, it has been concluded that for optimum residual stress was obtained with small feed rate and larger cutting speed.

Zhang Xuepinga [12] has optimized process parameters for residual stress after hard turning. The cutting conditions in the turning were speed, depth of cut, feed. He used DOE based on a Taguchi L9 array,

X-ray diffraction method is used to test the residual stress. Hardened steel was used in this investigation. The testing results confirmed that residual stress is in compressive in behavior and measured up to 0.1mm deep. It was observed that the rotation speed has a major considerable impact, after the depth of the cut. After performing the validation test the researchers found that the taguchi method is systematic and efficient tactic for optimization.

Sanjeev Saini [13] has been presented as a model to study the effect of the cutting condition and nose radius on axial, tangential and circumferential residual stresses in hard turning. Here ceramic tool is used to turn hard material. The DOE based on RSM and test results further analyzed using ANOVA. To test residual stress X-Ray diffraction technique was used. The researchers concluded that using the model the value of residual stress can be predicated also, concluded the following observations.

- As feed increased axial residual stress shifted from compressive to tensile. The magnitude of compressive stress increased with increase in depth of cut.
- The most influencing factor which affects the tangential residual stress is the depth of cut
- Not only depth of cut but feed plays a vital role in circumferential residual stress.

S. Carusoa [14] has investigated the effect of the tool cutting tool geometry, workpiece hardness, work rotational speed, and microstructure changes on the residual stresses in hard machining. X-ray diffraction method used to test in-depth residual stresses. The profile of residual stress checked in axial as well as circumferential directions. It was concluded that not only the axial but the circumferential residual stresses observed deep with increasing cutting speed. Turning parameters and the microstructure alterations on the residual stress profiles were observed as below in Figure 7.

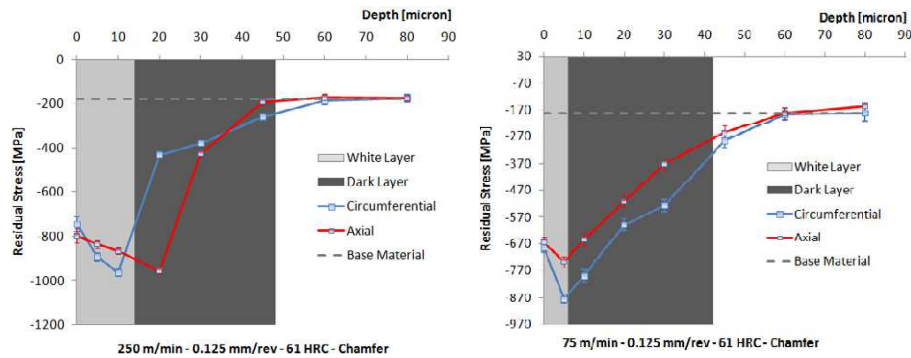


Figure 7: Microstructure Changes on Residual Stress Profiles

Meng Longhui [15] has been applied finite element method to find an optimum length of the workpiece. Researchers have concluded the study with

- Finite Element Method would be applied to correct the stresses determined by the X-ray diffraction method.
- Residual stress is compressive in both metal cutting and feeds direction.
- The turned workpiece was annealed at the temperature of 600 °C and stress released approximately 85% can be achieved near the surface in both directions.

Milling

Jiann-Cherng Su [16] has presented a model to predict induced residual stresses after milling operation. Milling operation conditions used are Speed, feed, depth of cut, cutting tool geometry, workpiece material properties. The model includes cutting force and generated heat to predict the residual stress. The residual stress is observed in compressive in nature. The magnitude of residual stress is the maximum in the analytic method.

Xinda Huang [17] has presented a systematic model for residual stress inside milling. The method used to predict the residual stress was incremental elastoplastic. Regular X-ray diffraction method used to test the residual stress. The residual stress in flank milling is the major function of the speed of the cutting point of the milling tool. The effective cycle time and significant value of the residual stress values are mainly influence due to feed and depth of cut respectively. The residual stress is compressive in nature in the feed direction.

Junteng Wanga [18] has investigated effect cutting conditions on the residual stress in milling operations. The milling tool used in this operation was ball end cutter. This study includes coolant and cutting axis angle. The results show that residual stress measured to 80 μm under the milling surface. Also, the researchers studied plot Residual stress vs. cutting parameters.

M Abdelkrim [19] has experimentally analyzed the significance of milling process parameters on process temperature and residual stresses generate. Here he used RSM method for design of experiments. The residual stress generated is compressive in nature in both x & y-direction. The error accuracy between predicted and measured values of milling temperature was 4.75 %. Not only spindle speed but the depth of cut is main influencing parameter during residual stress and the process temperature.

N. Masmiaati [20] has experimentally investigated the effect of different parameters on milling operation on an inclined surface. Taguchi optimization method was used in this research. Surface inclination, axial depth of cut, radial

depth of cut (shown in figure 8), speed, and feed these parameters are used for the optimization purpose. The research concluded the hardness of the inclined surface is directly proportional and residual stress inversely proportional to inclination angle. As the inclination increased the residual stress move to towards tensile. Whereas axial depth of cut and cutting speed has minimum persuade on microhardness and residual stress.

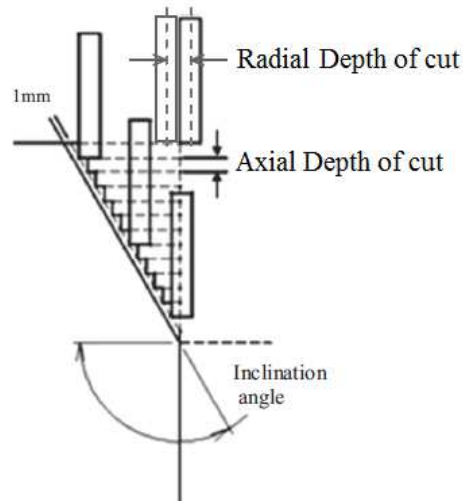


Figure 8: Machining

Grinding

Konstantinos Salonitis [21] has presented the model to predict the residual stress profile. The results observed were confirmed for grinding with coolant and without coolant. The researchers also developed a FEA model. The results confirmed with experiments and found the same profile. There is a very minor error in the FEA model and the experimental results.

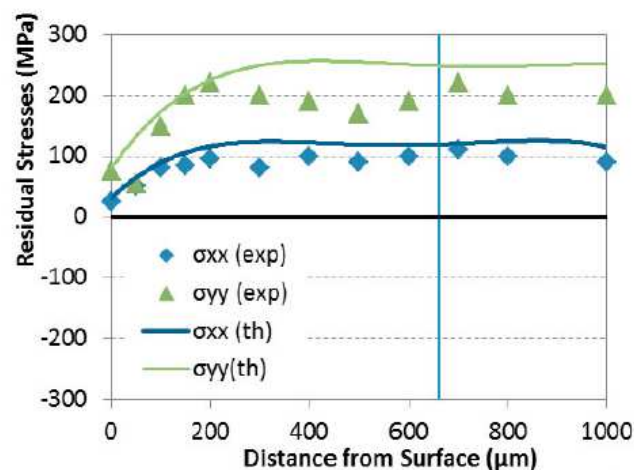


Figure 9: Residual Stress Profile in Dry Grinding

A. Juy [22] has studied the effect of surface residual stresses on the doped surface. The surface was TPZ doped. After that, the surface has been ground under different load conditions. The observed depth of surface residual stresses was up to 10 μm . The study concluded not only strength but the resistance also increased due to the residual stress generated by grinding and TZP doping.

Metal Joining Process and Residual Stress

Tae-Kwang Song [24] has presented total wall thickness welding residual stress profile. In this study, dissimilar material plates were welded. The metals welded here are alloy steel and austenitic stainless steels. Metal joining residual stress analysis was performed using FEA.

Yashar Javadi [25] has studied and optimized the residual stress generated in Friction Stir Welding (FSW). In this study, non-ferrous material sheets were used. For optimization welding parameters feed rate, rotational speed, pin diameter, and shoulder diameter were included. The optimization technique major influences the outcome of the welding parameters on longitudinal residual stress. The ultrasonic residual stress testing technique was used to quantify the stress magnitude. The test results were verified using the hole drilling technique. The optimization study concluded that the location of maximum residual stress was precisely obtained by ultrasonic machining. In this study, the maximum residual stress has occurred at the starting end of the welding. The major considerable parameter on the residual stress was feed rate. There was no considerable effect of pin and shoulder diameter on the friction stir welding. The overall reliability of study using Taguchi technique and ultrasonic testing was found very useful.

S.A.A. Akbari Mousavi [26] has been analyzed the residual stress generated in Tungsten Inert Gas welding. 2D & 3D FEA was used to analyze the process. The result of the geometry of groove on the distribution of residual stress dissemination was predicted. The observed results illustrated that higher tensile residual stress observed for 'U' shaped groove and less for 'V' shaped.

C.C. Tutum [27] has presented the optimization of friction stir welding process parameters. Genetic algorithm technique was used for optimization. The process was optimized to reduce the residual stress generated and increase the welding speed.

You-Chul Kim [27] has carried out welding experiment and exemplified the deformation and residual stress generated. The material used for welding was very high strength steel. Bead-on-plate welding was carried out using LBW. The results show that the residual stress generated in the direction to the weld line is tensile in nature. The residual stress generated is compressive in nature at the position normal to the welding line direction.

Non-Conventional Machining Method and Residual Stress

D. Arola [29] has been analyzed the effect of machining condition and material characteristics on the residual stress generated in abrasive water jet machining. In this kind machined component compressive residual stress observed. The abrasive particles in the process play a vital role while there was no significant effect of cutting pressure on residual stress.

Bulent Ekmekci [30] has conducted experimental analysis to test the residual stresses. The experiment concluded that high residual stresses are generated by EDM. The magnitude of residual stress is higher in heat affected zone. The machining parameters were not affected by residual stress pattern.

G.A. Moraitis [31] has developed 3-dimensional mathematical models to envisage residual stress in Laser Beam Machining (LBM). All the mechanisms related to heating and cooling were taken into account while establishing the mathematical model.

RESIDUAL STRESS MEASUREMENT

The induced residual stresses are stationery and stable in nature [2]. These stresses may be unfavorable to the recital of a component. On the other hand, positive residual stresses can be introduced purposely. Forecasting residual stresses are thornier than the in-service stresses on which they overlay. Then, it becomes essential to have trustworthy methods for the quantify of these stresses. In general, the method of measuring residual stress classify as destructive and nondestructive techniques

Residual stress is generated in many components which will be undergoing different manufacturing process. Over the decades the huge number of experimentations has been conducted to examine residual stress. There were diverse techniques have been established to test residual stress. Residual stress is not only complex but highly dynamic to envisage. The working stresses are cover up residual stress or vice versa. It will become imperative to select method to test residual stress [31]. The different techniques for testing the residual stress is classified in the fig.9 shown above. Each method is having its own advantages and disadvantages. Depending upon the depth affected by residual stress and the accuracy the technique will be selected. As per the requirement and requirement of test piece the destructive, non-destructive or semi-destructive technique will be applied. [32] [33]. There are certain criteria must be considered while selecting the appropriate method of testing.[34]

1. Non-destructive
2. Resolution.
3. The depth of measurement.
4. Stress direction.
5. Reliability.
6. Cost.

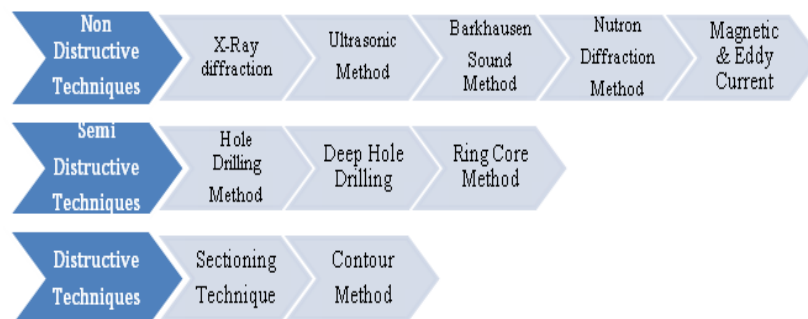


Figure 10: Different Techniques for Residual Stress Testing

Patrik Šarga[36] compared between two semi-destructive techniques; ring-Core & hole drilling technique [35]. The behavior of plasticity property on residual stress studied by using the contour technique. Quenching process applied to generate residual stress in the test sample. The destructive technique; contour technique is used to test the residual stress further the technique is simulated by FEA and the results were compared. It was concluded that both the results were good agreement [36]. M. B. Prime [38] has presented the contour technique of residual stress testing. The test piece is cut into two pieces and the new profile generated for the new surface is used to test the residual stress. Edoardo Capello [39] has presented the correlation between parameters and residual stress in the turning process. For testing the residual stress non-destruction technique; X-ray diffraction technique was used. J. Gauthier [40] has been tested residual stress of using Magnetic Barkhausen Noise technique. The accuracy of the technique was recorded as ± 25 MPa subjected to appropriate calibration of the instrument. The recorded test results were compared with X-Ray diffraction method. Z. Wu [43] has

proposed a simple and accurate method to determine residual stress. This method involves the combination of moiré interferometer, Twyman–Green interferometer, and hole drilling method. The proposed method will be useful to measure residual stress by applying three-dimensional displacement data at a single point.

STRESS RELIEVING

To enhance the product service life it needs to relieve the residual stresses generated. There are different residue stresses relieving processes. The application depends upon the depth of the residual stress from the machined surface. There are huge researches done on the use of the appropriate process for residual stress relieve from the component. To forecast the residual stress in the component Finite Element Methods also used.

Rearrangement of residual stresses is a competent approach to recovering the engineering properties of parts and structural elements. Stress relieving is carried out on manufactured parts to condense residual stresses. Also, it reduces the threat of parameter changes in the next manufacturing stage of a component.

Metal cutting, as well as deformation, will cause residual stresses in the material. This phenomenon will cause superfluous changes if keep uncontrolled. To diminish stresses after metal cutting and the peril for parameter changes the component can be stress relieved.

Such a stress relieving is carried out after the first stage of the manufacturing process. Stress relieving process is normally carried out after rough machining. The components having very close dimensional tolerances supposed to be stress relieved. Fabricated frames must be stress relieved to stable against deformation.

Compressive residual stress at the surface is beneficial whilst tensile residual stress at the surface is harmful. There are many ways to get rid of tensile residual stress at the surface. The residual stresses are not always useful in a few cases is harmful also.

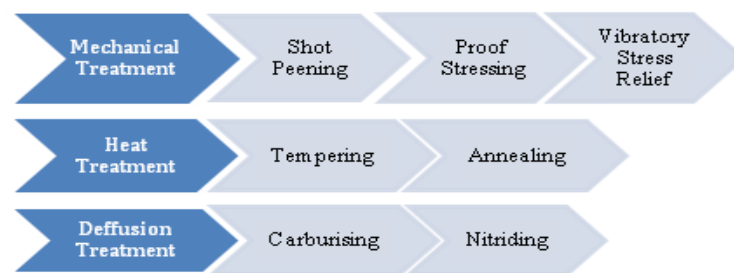


Figure 11: Residual Stress Reliving Technique Classification

Abdallah Hage Hassan [44] has used vibratory stress relief method for rectangular steel bar. The residual stress was checked before and after the VSR. From the experiment, it was concluded that the VSR reduced the residual stress. Also, he established equation to predict the magnitude residual stress after VSR. Delin Rao [45] has measured the residual stress before and after VSR for rails of a magnetic levitation (maglev) transport system. The residual stress was reduced by 30 % after VSR. Y.P. Yang [46] was developed an FEA model to envisage residual stress and simulate the vibratory stress relief. Resonant and non-resonant vibration stress relief can be applied to relive the residual stress. The experimentation concluded that vibration amplitude and vibration mode are major influencing parameters to minimize residual stress. Time for vibration doesn't play a vital role in residual stress. M. Akiyama [47] has been proposed a new method to reduce residual stress after the cold bar drawing process. In this method, the axial tension is applied after the drawing process. The

magnitude of tension is a major influencing factor to manage residual stress in bar or wire. M. Jafari Vardanjani[48] investigates VSR to minimize residual stress. From the experimental study, it was concluded that applying VSR method residual stress can be minimized. He also developed a mathematical model depending on plasticity theorem. The experimental results and results from mathematical model followed the similar move. The residual stress can be minimized to 70 %. X.C. Zhao [49] has generated a FEA model for VSR method. Vibration frequency and amplitude of load had an influence on reducing the residual stress. It was concluded that FEM can be proposed to appreciate VSR method and optimize the parameter of VSR process.

SUMMARY

Residual Stress

Residual stress generated in various manufacturing process forecast has been an area of research from last five to seven decades. Residual stresses can be observed due to many causes. It may be generated due to the method used to make the component. Manufacturing processes are major general causes of residual stress. All the manufacturing and joining processes such as forging, casting, turning, milling, grinding, welding, heat treatment, and non-conventional machining initiate residual stresses into the component. This could be caused by confined to a small area yielding of the material. The origin of residual stresses in a component may be due to

- Discrepancy plastic flow
- Discrepancy cooling rates
- Stage transformations with volume changes etc.

Residual stresses classified as

- **Type I:** Macro residual stress.
- **Type II:** Micro residual stress.
- **Type III:** Micro residual stress that subsists inside the granule.

Residual Stress Measuring Methods

Different destructive and non-destructive methods of measuring residual stress available. Depending on the depth of the residual stress measurement the method will be decided. In most of the cases the residual stress investigation useful to increase consistency and service life of the component. From last few years, positive developments have been noted in the field of traditional and new methods of measuring the residual stress. Various NDT tools for residual stress measurement such as ultrasonic, X-ray diffraction, eddy current, the Barkhausen sound method has been developed and successfully used in various applications. There are different destructive methods also available to measure the residual stress. The distractive methods are sectioning technique and the contour method.

Stress Relief

Basically, mechanical, thermal and diffusion techniques are available to relief the residual stress. Vibratory Stress Relief method is more beneficial and has major advantages than the thermal stress relieving methods. The fact behind this is reduced power consumption and fewer chances of distortion due to heat. Also, no pollution effect due to VSR method wrt thermal stress relief. Resonant and non-resonant vibrations can be used to relieve residual stresses. Resonant & Non-

resonant VSR produces the greatest residual stress relief.

CONCLUSIONS

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